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Research on Fatigue Characteristics of Bonding interface of Solid Rocket Motor Propellant

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Abstract—With the continuous expansion of the combat mission of the Chinese Navy, the solid rocket motor will be on duty at sea for a long time. During the service period of solid rocket motor, the bonding interface will bear a large number of cyclic fatigue loads. According to the design test, the influence of the strain amplitude and frequency of loading on the bonding interface was studied. The results show that the cyclic loading frequency made no difference on the cyclic damage number in the high frequency. The natural logarithm of the cyclic loading times and cyclic loading accord with linear fitting equation.

1. Introduction

Solid rocket motors have the characteristics of easy maintenance, long-term storage, simple structure and low cost. So most missiles in the world use solid rocket motors as their power units. The interface of solid rocket motor is easy to damage. With the continuous expansion of the combat mission of the Chinese Navy, the solid rocket motor will be on duty at sea for a long time. When the solid rocket motor is on duty, the propellant grain and interface experience complex vibration loads. The solid rocket motor's reliability will degrade in the long term vibration environment. The interface of the solid rocket motors could result in debonding in this environment. So how to establish a scientific and effective evaluation model has become a research hotspot [1-5].

In order to evaluate solid rocket motor technical status, the stress and strain must get by current non-destructive inspection methods. Now the stress-strain of solid rocket motor can be obtained by finite element numerical simulation. These data can confirm the key parts of solid rocket motor for evaluating solid rocket motor technical status [6-9].

Domestic and foreign scholars [11-14] have carried out finite element analysis and research on the situation of solid rocket motor long-term storage, road transportation, carrier on duty and so on, and judged its reliability according to the damage criterion of grain, it provides a certain basis for motor life evaluation. However, the input condition of vibration load is low frequency vibration load, especially the period of ship motion is 10s, so the measured vibration data is not taken as the input condition. The creep damage of grain and adhesive interface of vertical storage solid rocket motor was investigated by Wang Yongshuai [15]. Wang Xin [16] has carried out the finite element calculation under the combined action of motor curing cooling, long term gravity and low frequency vibration, and obtained the distribution law of stress and strain of grain. Although the acceleration load produced by the rocking

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motion of the ship is relatively small and cannot reach the limit load of the solid rocket motor, the long-term effect of this small stress load may also produce greater damage. Because the propellant grain is a multi-component polymer, it is mainly composed of polymer matrix and a large number of solid oxide particles and metal fuel particles. Due to the mechanical mixing of solid particles in the matrix, the propellant will be irreversibly damaged under various external small stress loads. On the meso-level, the damage includes the fracture of the matrix structure and the dewetting of the interface between the particles and the Matrix, and these meso-damage may converge into macro-cracks and debonding defects.

The interface debonding is the mainly failure model in solid rocket motor. One third of solid rocket motor cannot use in this reason[17].So the ignition process can be mainly affected by the interface property in solid rocket motor. The chemical debonding quality were fully researched ,but fatigue characteristics of bonding interface need to research deeply [18-22].

Although the failure of propellant debonding interface is an important failure mode of solid rocket motor. But to push the research on the damage of the adhesive interface only focuses on the changes of the physical and chemical properties of the adhesive interface. Research the mechanical performance index of debonding interface often pays attention to the ultimate performance index, such as propellant pull-off stress and maximum shear stress, etc. Therefore, it is necessary to carry out the fatigue damage test of propellant debonding interface, and pay attention to the effect of vibration load. The universal material tensile testing machine and shaking table were used . The shear fatigue test scheme of debonding interface was prepared and designed to obtain the debonding interface of composite solid propellant fatigue damage performance.

2. Test Specimen Manufacture and Test Design

2.1. Test Specimen Manufacture

In order to research the fatigue characteristics of the interface, the test specimen must be firstly designed. the geometry of specimen is shown in Figure 1. The shadow part in the specimen is the propellant, the rest part of it is the iron . The interface of the specimen is as same as the interface of solid rocket motor. The temperature was controlled within 20 ± 2°C during experiment. The relative humidity was controlled under 70% during experiment. The velocity of tensile test was 50mm/min.

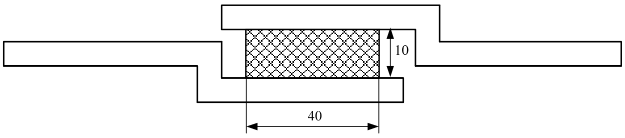

Figure 1. Example of a figure caption.

In the test progress, the loading model and distortion of the specimen is shown in Figure 2. In order to expediently deal with the test data, the definition of shear stress can be calculated by (1).

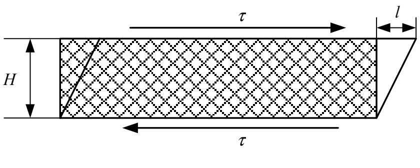

Figure 2. Distortion of the specimen.

$$\gamma = \tan(l/H) \tag{1}$$

In order to confirm the shear strain amplitude in cyclic loading test, the tensile shear experiment was firstly made. The style of specimen is shown in Figure 1. The curve of stress-strain curve is shown in Figure 3. The maximum shear strain $\gamma_{\max}$ is 0.4692 and the maximum stress $\tau_{\max}$ is 0.4863MPa.

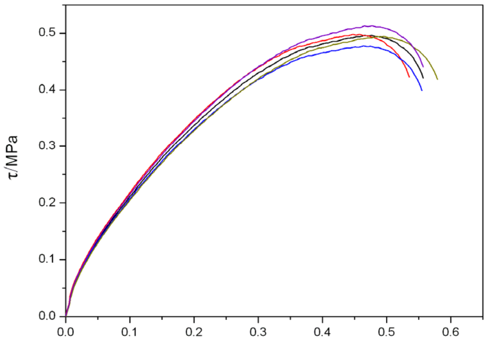

Figure 3. $\tau - \gamma$ of propellant interface.

2.2. Test Design

In order to maintain research unity, the style of the specimen is shown in Fig.1. One side of the specimen is fixed on the vibration table, the other side of the specimen is fixed on clamp. The vibration table is shown in Figure 4. The specimens are divided eighteen groups.

Figure 4. ES-10-Amber vibrating table.

Five specimens were made in every contain. Zero was selected for each average strain. According to researching the test data, six strain amplitudes were confirmed. The six shear strain amplitudes $\Delta\gamma$ were 0.2, 0.25, 0.3, 0.35, 0.4 and 0.45. The cyclic loading frequency selected 5(Hz), 10(Hz) and 15(Hz) in every shear strain amplitude. The cyclic loading wave shape is a sine wave. In the process of the experiment, cyclic loading number is recorded when the specimen is destroyed.

2.3. Results of test at different strains levels and frequency.

When the specimens were damaged , it can be research by observing fracture surface. The damage figure is shown in Figure 5. Because the interface is made of matrix and solid grain, the stress concentration can occur. The damage model of the interface is the “deweting” of matrix and solid grain. The former situation caused microcrack between liner and propellant. The microcrack can develop macrocrack between liner and propellant, which can cause the damage of the interface between liner and propellant.

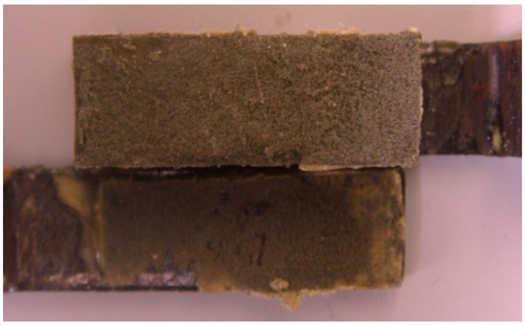

Figure 5. Vibrating damage process of interface.

The result of test is shown in Table 1, which can be used to research the frequency cyclic loading effect on the vibrating damage of specimen.

TABLE 1. VIBRATING FATIGUE DAMAGE TEST RESULTS OF INTERFACE

Group Number	γ_m	$\Delta\gamma$	Frenquecy(Hz)	Damage Number (N)
1	0	0.2	5	195883
2			10	185348
3			15	191382
4		0.25	5	34161
5			10	33963
6			15	36058
7		0.3	5	7005
8			10	6654
9			15	7014
10		0.35	5	1253
11			10	1178
12			15	1268
13		0.4	5	229
14			10	241
15			15	234
16		0.45	5	47
17			10	46
18			15	50

3. Frequency cyclic loading effect on result of the test

In order to research the change of linear fatigue performance in different high frequency, the relative error can be calculated in (2). δ is the relative error of the data. $N(\Delta\gamma, f)$ is the specimen damage number, when shear strain amplitude is $\Delta\gamma$ and cyclic loading frequency is f. $\overline{N}(\Delta\gamma)$ is the specimen mean damage number, when shear strain amplitude is $\Delta\gamma$.

$$\delta = \frac{\left|N(\Delta\gamma, f) - \overline{N}(\Delta\gamma)\right|}{\overline{N}(\Delta\gamma)} \times 100\% \tag{2}$$

The relative error of the testing data can calculated in (2), the results can be shown in Figure 6.

The Figure 6 can be shown that the relative error of the testing data in different cyclic frequency with the same shear strain amplitude is no more than 5%. So the conclusion can be acquired that the cyclic loading frequency made no difference on the cyclic damage number in the high frequency.

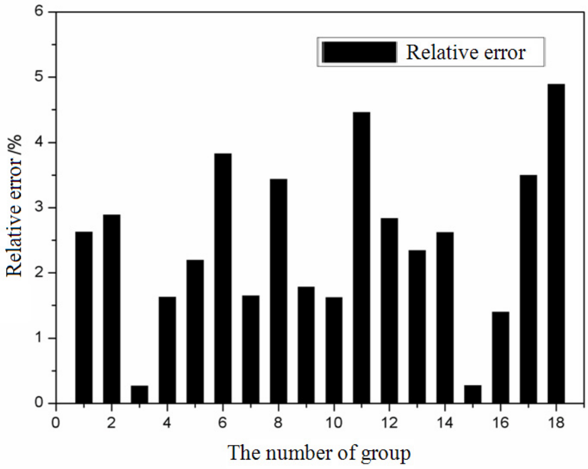

Figure 6. Cyclic frequency influence on test data error.

In order to research the experiment data , the method of linear fitting can be used. Because the literature [21] used this method to research creep mechanical behavior of the propellant. Because the cyclic loading frequency made no difference on the cyclic damage number in the high frequency, the data of shear strain cycles in Frequency 5Hz was used. According to data analysis, the natural logarithm of fatigue damage times was taken. The fitting equation of interface fatigue characteristics was used as (3). The fitting curve was shown in Figure 7. The equation fitting coefficients were shown in Table 2.

$$Y = A + BX \tag{3}$$

In (3), X is the natural logarithm of cyclic damage number, Y is the shear strain level, A and B are the equation fitting coefficients.

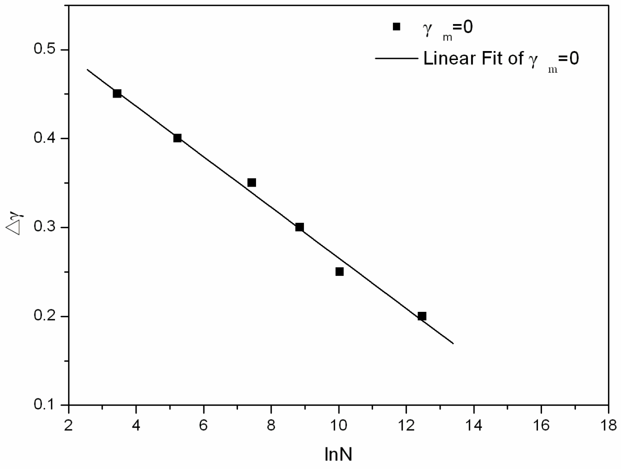

Figure 7. $\Delta\gamma - \ln N$ of interface

TABLE 2. COEFFICIENTS OF THE EQUATION

A	B	correlation coefficient
0.55011	-0.02844	-0.99572

4. Conclusions

In order to research the cyclic fatigue of the interface, the fatigue test was designed in different frequency and shear strain levels.

The cyclic loading frequency made no difference on the cyclic damage number in the high frequency.

The natural logarithm of the cyclic loading times and cyclic loading accord with linear fitting equation.

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